Biomass accident investigations – missed opportunities for learning and accident prevention

Hedlund, Frank Huess

Published in:
Proceedings of the 25th European Biomass Conference and Exhibition

Link to article, DOI:
10.5071/25thEUBCE2017-4AV.2.45

Publication date:
2017

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Hedlund, F. H. (2017). Biomass accident investigations – missed opportunities for learning and accident prevention. In *Proceedings of the 25th European Biomass Conference and Exhibition* (pp. 1804-1814). ETA-Florence Renewable Energies. https://doi.org/10.5071/25thEUBCE2017-4AV.2.45

BIOMASS ACCIDENT INVESTIGATIONS – MISSED OPPORTUNITIES FOR LEARNING AND ACCIDENT PREVENTION

Frank Huess HEDLUND
COWI and Technical University of Denmark, (DTU)
DK-2800 Kongens Lyngby, Denmark. fhhe@cowi.com and fhuhe@dtu.dk

ABSTRACT: The past decade has seen a major increase in the production of energy from biomass. The growth has been mirrored in an increase of serious biomass related accidents involving fires, gas explosions, combustible dust explosions and the release of toxic gasses. There are indications that the number of bioenergy related accidents is growing faster than the energy production. This paper argues that biomass accidents, if properly investigated and lessons shared widely, provide ample opportunities for improving general hazard awareness and safety performance of the biomass industry. The paper examines selected serious accidents involving biogas and wood pellets in Denmark and argues that such opportunities for learning were missed because accident investigations were superficial, follow-up incomplete and information sharing absent. In one particularly distressing case, a facility saw a repeat accident, this time with fatal outcome, still without any learning taking place. The paper presents some information on other biomass accidents in Denmark, mostly involving biogas from anaerobic digestion. Details are lacking however, precisely because the accidents were insufficiently investigated and results not communicated. The biomass industry needs to pay more attention to safety. Utmost care should be taken to avoid so-called media-shifting i.e. that the resolution of a problem within one domain, the environmental, creates a new problem in another, the workplace safety domain.

Keywords: biogas, wood pellet, explosion, ATEX, accident investigation, lessons learned, inherent safety

1 INTRODUCTION

The views of this paper run along three main lines of arguments:

- that currently, the biomass industry gives insufficient attention to safety and major accident hazards;
- that sub-optimalities have to be addressed, particularly those related to so-called media-shifting; and,
- that accident prevention opportunities are foregone due to superficial investigation when accidents do take place, because root causes are not identified and sharing of lessons learned is limited or absent.

1.1 Insufficient attention to safety

The number of major accidents in the bioenergy production and raw materials supply chain is not only increasing but seemingly growing faster than the quantity of energy produced [1]. Safety problems deserve more serious consideration and safety, in a general context, is worthy of being treated as an actual component of sustainability [2].

Biofuels have been the subject of continuous research work world-wide. Earlier studies have argued however, that apart from e.g. material compatibility issues, only limited consideration has been given to safety [2].

Several reasons for this state of affairs have been offered [3]:

(1) It is commonly believed amongst biofuel manufacturers that process safety can be achieved merely by application of common sense;

(2) There is inconsistency in applicable regulations;

(3) There are low skills and competence issues associated with the entry of new manufacturers; and

(4) There is limited information available on the process hazards and minimal appreciation on the risk involved in the production of the biofuels

Other authors argue that due to perceived simplicity of the chemical process, attention to safety is frequently omitted as is basic safety training of the personnel [4] and that poor safety culture is an issue [1]. For biogas production in particular, safety challenges and sustainability issues have become a concern [5].

1.2 Safety, a legitimate objective in industry?

Co-incidentally, the call-for-papers to this EUBCE 2017 international biomass conference provides support to the basic argument of this paper, that there is little attention to safety and limited appreciation of hazards in the biomass industry.

To classify conference contributions, the organizers have compiled a list, which as per April 2017 had 470 keywords entries. The topic of safety is conspicuous by its absence – there is not a single keyword related to safety in this long list.

The closest match is "security". Security measures relate to physical protection however, such as safeguarding an asset from unauthorized access and acts of malevolence. Security is much different from safety [6]. The following standard keywords related to biomass safety are absent in the list: safety, accident investigation, fire, combustible dust explosion, ATEX, emergency response, firefighting, oxygen depletion, off-gassing, toxic gas hazard, hydrogen sulfide and carbon monoxide.

This is remarkable bearing in mind that the conference has global attendance, with 800-900 contributions from 3800 authors from 80 countries.

1.3 Media-shifting

Environmental interventions may be undertaken with insufficient attention paid to workplace safety [7], [8]. Two types of sub-optimalities can be identified:

1) media shifting, which occurs if the 'resolution' of a problem within the environmental domain gives rise to new, and unforeseen, problems within other domains, specifically the workplace safety domain; and

2) a missed opportunity, which occurs if an opportunity exists for improving both environmental and occupational health and safety performance, but a less optimal solution is chosen that only addresses environmental performance.

Cite as: F.H. Hedlund, Biomass Accident Investigations - Missed Opportunities for Learning and Accident Prevention, in: L. Ek, H. Ehrnrooth, N. Scarlat, A. Grassi, P. Helm (Eds.), Pap. 25th Eur. Biomass Conf. 12-15 June 2017. Setting Course a Biobased Econ., Stockholm, Sweden, 2017. ETA-Florence Renewable Energies: pp. 1804–1814. doi:10.5071/25thEUBCE2017-4AV.2.45

1.4 Accident investigation and learning

Having paid the price of an accident, we should use the opportunity to learn from it. Entire books have been dedicated to learning from accident case stories in the process industry [9]–[11]. The benefits of such learning are obvious – to avoid repetition, and to share the lessons learned in order to minimize the number of times the same lessons have to be learned.

What is not so obvious, however, is how to make this seemingly simple and straightforward idea work in practice [12], [13]. This challenge is reflected in common aphorisms, such as Santanyana's: Those who cannot remember the past are condemned to repeat it.

1.5 Causes

The search for accident causes has been likened to peeling an onion [14]. The skin represents the immediate technical causes but beneath lies layers and layers of underlying causes such as weaknesses in the management system, each contributing with important insights for prevention. Much theory exist on this subject, e.g. [15], [16]. It suffices here to stress that both immediate and underlying causes should be sought after an accident.

As will be argued later in this article, the biomass industry fares badly in this respect – investigations are superficial.

2 METHOD AND MATERIALS

The first sections of the paper examine three serious Danish biomass accident case stories in detail. The case stories have been selected for their following characteristics:

(1) They have major accident potential, resulting in fatal or near-fatal injury and they clearly have multiple fatality potential.

(2) They were poorly investigated, with direct causes being only superficially identified or not identified at all, and underlying organizational issues ignored.

(3) There is sparse information on the etiology of the accidents in open sources, in some cases resulting in basic facts being inaccurate or misleading.

(4) Repeat accidents took place at a later stage.

Primary sources are, unless otherwise indicated, dockets of the Danish Working Environment Authority and the police obtained through the Danish equivalent of a Freedom of Information Act. Media reporting may serve as supplementary sources.

3 ACCIDENT 1: EXPLOSION OF BIOGAS DIGESTER

3.1 The digester

In 1990, a biogas digester at Vejle municipal wastewater treatment plant (WWTP) in Denmark exploded. The anaerobic digester processed regular municipal sewage sludge.

At the time, the WWTP had four anaerobic digesters, one gasholder tank and one tank for processed sludge. Digesters #3 and #4 were identical and built in the early 1970s using concrete slipform construction methods. A rectangular building between the two digesters held shared technical installations and access stairways.

The digesters were vertical cylinders with a cone shaped roof and a cone shaped bottom. An upper horizontal ring beam between the cylinder and the top cone helped distribute structural loads. In a cut-through drawing (fig. 1), the digester would appear as a hexagon.

A circular cavity wall circled the digester. Leca-blocks were used for the inner-wall and masonry red brickwork for the outer wall. For architectonical and decorative purposes, the circumference of the outer brick wall was interrupted every five meters or so by slender concrete columns in series of three to break visual monotony. The columns were purely decorative and carried no load.

At the upper part of the digester tank, a parapet provided circumferential structural support to a horizontal roof deck. The circular cavity between the horizontal deck and upper cone of the digester served as a utility corridor for pipes and other technical installations. The parapet was an extension of the circular exterior wall, which covered the digester's thermal insulation. The parapet continued vertically above the upper ring beam and extended about 1 m above the horizontal roof deck.

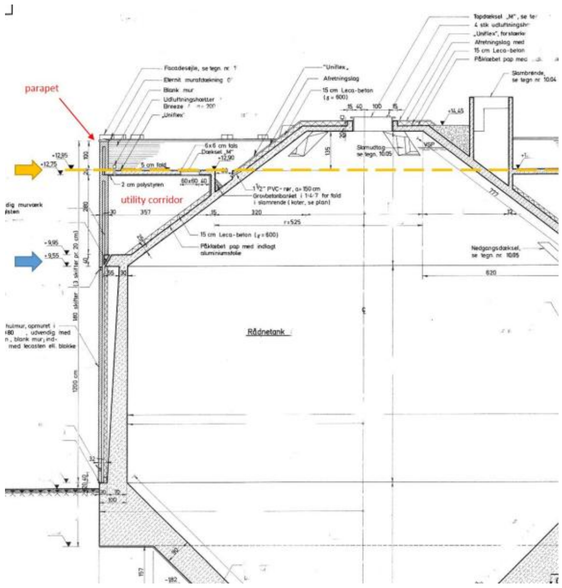

Figure 1: Part of cross-sectional drawing of the accident biogas digester. The blue arrow marks the horizontal ring beam. The yellow arrow and dotted line mark the roof deck supported by a parapet. Five contractors were present at the roof doing asphalt roofing work when the explosion took place. Drawing courtesy of Krüger, Denmark.

3.2 Roofing work

Digesters #3 and #4 were in need of roof repairs. For reasons that are no longer known, asphalt roofing was decided upon. This type of roofing material is a membrane made of a felt or fiberglass mat saturated with bitumen. The roofing material is applied using a propane fired torch which partly melts the bitumen mixture on the underside of the membrane and glues it to the roof.

3.3 Prior planning of roof work

Planning of the roof work started more than two months in advance. A project team was assembled and at least one meeting was held with representatives from the roofing contractor, the WWTP, the Danish Working Environment Authority, the municipal fire department, an external occupational health and safety specialist from a large engineering consultancy, and others.

Work would start on Digester #4. The following procedure was agreed upon:

- No new sludge to be fed to the digester two weeks before the work was to commence
- All roof hatches to be opened one week before the work, in order to gas free the digester (natural ventilation)
- All roof hatches to be sealed closed and valves to the neighboring digester 3, and other biogas systems, to be locked closed.
- While the work is carried out, any surplus gas in the digester to be vented to a safe location. A hose, length 8-10 m, to be fitted to the digester's open 8" top vent valve. The hose to terminate at the perimeter and extend no less than 3 m above the roof. Bio methane is lighter than air and hence buoyant, which would ensure safe natural dispersion.
- Al all times should the hose outlet be downwind the work site, to keep the worksite free of gas
- At all times should an explosimeter be at the worksite. The work must stop immediately if flammable gasses are detected (alarm level 15 percent of the lower explosion limit of bio-methane).

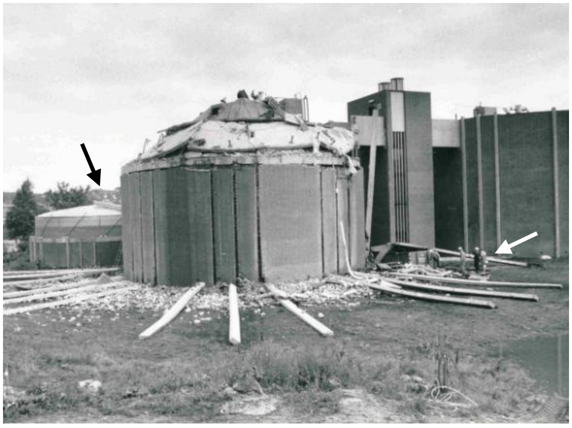

Figure 2: Aftermath. The accident Digester #4 center, the identical and apparently undamaged digester #3 to the right. The digester's roof deck collapsed and two roofing contractors fell down 11 m. At least one of the decorative concrete columns fell onto the gasholder tank behind the accident digester at center left (arrow).. Note persons for scale at center right (arrow). Photo courtesy of Vejle Amts Folkeblad.

3.4 The explosion

In the early morning of the third workday, on August 22, 1990, Digester #4 exploded. At the time of the explosion, five contractors were present doing asphalt roll roofing work.

The explosion either blew the parapet away or dislocated it, causing it to collapse (Fig. 2). With the peripheral structural support gone, the horizontal roof deck with the workers on top also collapsed (Fig. 3). Two workers fell 11 m and landed in the debris zone below. They suffered very seriously injuries, inter-alia serious head trauma. They survived but with debilitating permanent injuries.

Two workers suffered minor injuries as they fell "to a lower level", probably because they managed to cling onto what remained of the roof deck. Miraculously, one worker was unharmed.

Figure 3: The collapsed roof deck. A small section of the remains of the parapet, which provided structural support to the roof deck, is just visible to the left (arrow). Photo courtesy of Vejle Amts Folkeblad.

3.5 Cause

The investigation soon identified the cause. The hose fitted to the digester's 8" top vent valve was a simple flexible duct similar to those commonly used for household kitchen ventilation purposes – a plastic cover over a metal wire coil to shape a tube (Fig. 4). The hose did indeed terminate at the perimeter of the digester and was indeed elevated to a height of 3 m, but the hose was lying on the roof, unprotected. In a moment of inattention, a worker had grazed the flexible hose with his propane burner torch – the plastic had melted and the gas inside ignited. There was no flashback arrestor in the line and the flame could travel back into the digester, causing an explosion there.

3.6 Ignorance

A contemporary occupational health and safety magazine [17] expressed an almost heartbroken frustration with the fact that a glaringly obvious hazard was overlooked by all participants. Indeed, with the benefit of hindsight, gross ignorance in the planning phase is evident. Such ignorance however, when realized, is a prime candidate for information exchange of lessons learned and insights gained to prevent repeat accidents.

Basic combustion engineering knowledge regarding flammability limits seems to have been absent in the planning phase. The decision to open the top hatches in an attempt to free the digester of flammable gas is particularly distressing. Mixtures of gas and air will burn only if the fuel concentration lies within well-defined lower and upper bounds referred to as flammability limits. Had the top hatches not been opened and air not entered the digester, the gas in the digester would not have been in the ignitable range. With no ingress of air, a flashback into the digester would not have been possible and an explosion could not have taken place.

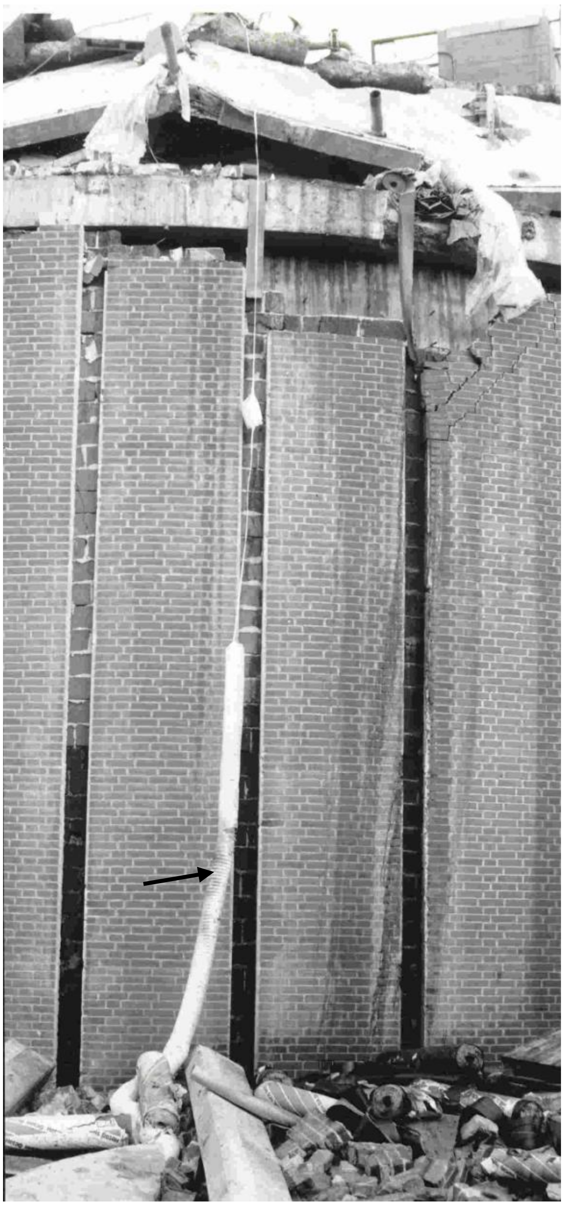

Figure 4: The "glaringly obvious hazard" (with the benefit of hindsight). The standard flexible duct of the same type commonly used for household kitchen ventilation purposes hangs from the roof (arrow), torn and burnt. It was fitted to the top valve to vent excess digester gas. The propane torch of an asphalt roofing contractor grazed the flexible duct, ignited the gas inside, and the flame flashed back into the digester, leading to explosion. Photo courtesy of Vejle Amts Folkeblad.

The decision to free the digester of flammable gas by opening the top hatches and rely on natural ventilation was also ill conceived. Although pure bio-methane indeed is lighter than air, and hence is buoyant, biogas is not. Significant quantities of carbon dioxide are created by the same anaerobic microbial processes that produce bio-methane, the typical volumetric concentration is about 1/3. The carbon dioxide molecule is denser than air and as a result, (dry) biogas often has a near-neutral density relative to air. It is not particularly buoyant and will mix only slowly with stagnant air.

The project team seems to have been singularly concerned with the risk for ignitable gas *at the workplace*, presumably because the main hazard identified was sources of ignition: the naked flame of the propane torches. The team's mental model of hazards seems to have been limited to where ignition sources were present, ignoring the hazard of ignitable gas inside the digester. This may reflect traditional explosion protection thinking prevalent at the time, which concerned itself with classification of areas to facilitate the proper selection and installation of εx (epsilon-x) classified electrical equipment to be used safely in those areas – i.e. to reduce the probability of ignition. Only with the ATEX Directive introduced later came a broader risk analysis based approach, the so-called safety principles, which directs attention to first, preventing the formation of flammable atmospheres, second, to reduce the chance of ignition, and third, to mitigate the severity of the consequences.

Mistakes in execution are also evident. The decision to use a standard flexible duct similar to those commonly used for household kitchen ventilation purposes is disturbing as is the practical implementation, with the hose lying directly on the roof, unprotected. The asphalt roofing contractors seem to have been clueless about hazards.

3.7 Forgotten

The accident is important not only for the lessons learned it provides, but also for the fact that basic knowledge about the event has passed into oblivion only 25 years after having taken place [18].

In 2014, a Google search for the accident would come back empty. The search tool REX at the Danish National Library would find nothing. Nor would Infomedia, a Danish proprietary search engine and media article repository that tracks about 1,900 Danish media.

In 2014, the staff at Vejle WWTP knew the accident had taken place but no one had any personal knowledge of the event and written records no longer exist.

Access to the records of the Danish Working Environment Authority and the police was requested through the Danish equivalent of a Freedom of Information Act. The docket obtained from the Working Environment Authority appears to be incomplete however, there is no investigation of the accident itself, only minutes of the many meetings held later, when asphalt roofing work was to be carried out on Digester #3. The police informed that their docket had been transferred to the Viborg branch of the Danish National Archives. With regrets, they informed that the docket could not be located, the archive box was empty.

Two specialist magazines with limited circulation each carried an article on the accident [17], [19]. The magazines could be retrieved only with much effort.

News media coverage was available at the microfiche archive at the Danish National Library in Copenhagen. Upon request, the regional newspaper Vejle Amts Folkeblad kindly retrieved photos from their archives and made them available for publication.

Perhaps the starkest evidence of oblivion is a 2012 safety document for a large Danish biogas facility covered by the EU Seveso Directive (lower-tier). In sweeping statements, the facility's safety document asserts that the literature is silent on biogas accidents.

3.8 Learning processes?

As stated above, ignorance, when realized, is a prime candidate for information exchange of lessons learned and insights gained to prevent repeat accidents. Opportunities for learning after the 1990 digester explosion appear to have been wholly missed however.

Lindberg et al. [20] offer a description of the CHAIN model for experience feedback, which comprise six activities (1) reporting, (2) selection, (3) investigation, (4) dissemination, (5) prevention, and (6) evaluation.

The model summarizes well-known concepts from the literature and underlines that learning from past accidents is truly a chain in the sense that the process as a whole fails if any one of its links fails.

In the 1990 Vejle accident some of the early links in the chain failed – and the accident was simply forgotten.

3.9 Repeat accidents

The French ARIA database [21] offers a brief description of a biogas digester explosion in Peschiera Del Garda (Italy) on March 12, 1997, which appears to share many similarities with the 1990 Vejle accident.

The site was a municipal wastewater treatment plant, the digester was made of concrete and roof "repair works" were being carried out. The accident description simply says that "residue gas" was present in the digester. Welding ignited the gas and the concrete digester exploded. Two workers were thrown from the roof and killed. A third worker fell into the digester and was seriously injured. There is no description of the circumstance and of lessons learned, if any.

In 1976 a concrete biogas digester exploded in Åkeshov (Sweden). A picture is provided in [22] and large chunks of concrete at the base of the tank indicate that either the wall or the roof has been severely damaged. There are no details.

Even cursory reporting of repeat accidents is compromised if incomplete or absent reporting of biogas accidents is the norm rather than the exception. Not much is known about the propensity to report. Experience from Denmark, detailed below, suggests that reporting is very poor indeed.

3.10 Value of information sharing

An accident investigation report with detailed analysis of causes, consequences and a rich discussion of how to prevent repeat occurrences is of obvious value to operators of similar units elsewhere and to the general community of safety professionals.

Even rudimentary knowledge that a certain type of accident has occurred in not without value either. Designers of anaerobic digesters have educated this author on why internal explosions in digesters are implausible, if not impossible. Most of their assertions were based on coherent technical rationales such as lack of oxygen in the headspace, that digesters are heated and the high humidity and large amount of water vapor in the headspace inerts the atmosphere there, that sources of ignition are absent, etc. But assertions could also be less sophisticated: "it has never happened" or "never heard of it". The mere knowledge of the existence of past incidents can cool such complacency.

Knowledge of past accidents can also help populate the list of possible scenarios and consequences to consider in risk analysis work. One generic risk analysis scheme for off-site risk assessment [23] include harm from emissions (i.e.. leaks) only, as does the generic ATEX approach in [24]. Own work (unpublished) and circumstantial evidence from cursory media reporting [25] suggest that blast overpressure from an internal explosion in a digester or a gas holder might also be relevant accident scenarios for off-site risk assessment. A third generic risk analysis scheme [26] for biogas risk assessment ignores the risk for H_2S poisoning, even though such fatal accidents have occurred. Additional unusual consequences may be considered. In 1976, for example, two sewage storage tanks exploded; the tank failed catastrophically and the gush of sludge killed a teenager and seriously injured an adolescent who were fishing nearby [27]. The unusual consequence is drowning in sludge.

3.11 Other Danish biogas incidents

Starting in 2003, the Danish Safety Technology Authority has issued an annual report with a list of accidents involving flammable gasses, biogas included. The reports are partly based on mandatory self-reporting of accidents that meet certain severity characteristics. The Authority also monitors news media reporting, based on automated screening of keywords. The authority does not investigate accidents.

A review of the Annual reports for 2003-2016 yields one biogas accident (years 2014 and 2015 are not included, reports were not available at the Authority's website): On Sept 2, 2005, at Hemmet a covered tank with degassed manure from a biogas digester "exploded". The biogas is believed to have been ignited by a powertool, when an employee drilled holes in the exterior tank wall to attach a fitting. There were no casualties. There are no details as to why gas was present outside the tank or the nature of the damage caused by the explosion. The brief description is probably based on media reports, which are notoriously inaccurate.

The supplementary information below is based on media reporting retrieved through Infomedia (a proprietary Danish media article repository) or Google.

On December 2, 1999, at Ribe, a severe storm caused a digester to collapse. The digester damaged a neighboring tank, probably another digester, and partly crushed to buildings. There are no details.

Late July 2002, a lightning strike had damaged the flare at Blåbjerg biogas. While the flare was out of service, waiting for spare parts, venting of (unburnt) excess biogas led to neighbor complaints about foul odors. An inspection by the municipality the day the flare was taken back into service discovered a "torn membrane" and a "faulty valve", which had leaked foul biogas for at least 1½ weeks. Details are hazy.

On Jan 8, 2005, the outer protective membrane of a double membrane gas storage holder at Blåbjerg Biogas in Nørre Nebel was torn and dislodged in a storm. There was no damage to the inner membrane and no release of biogas.

Around March 20, 2007, the outer protective membrane of a double membrane gas storage holder at Hashøj biogas collapsed in a storm. The storm dislodged the blower duct and overpressure was lost. A week or so earlier, a batch of Norwegian "wood oil" had killed the microbes in the digester, hence the inner membrane contained little or no gas. When overpressure was lost, the outer membrane collapsed. Apparently, the two membranes were not damaged.

Early September 2013 a silo with dried sludge at Bjergmarken WWTP exploded. It appears to be self-ignition and a subsequent pyrolysis gas explosion, i.e. biogas was not involved. There are no details.

On May 25, 2014, a biogas storage in Thorsø "burned down". Seemingly, an inflatable double membrane gas storage holder was ignited by a blower motor, which caught fire due to an electrical short (personal communication). Details are hazy however, and the information should be viewed with caution.

On August 6, 2015, several people were overcome by hydrogen sulfide fumes at Hashøj Biogas while unloading food waste. Media reports misstate the gas as NO_X and garble other basic facts. This author is in the process of preparing an article on this very serious accident.

On November 29, 2015, the storm "Gorm" severely damaged the exterior insulation on digesters at Holsted biogas. There was no release of biogas.

On May 20, 2009, give and take a few days, a biogas powered public transportation bus caught fire at Jernbane Allé, Vanløse. The fire services doused the bus with copious amounts of water but were much relieved when they learned that biogas (not fossil gas) was involved. "At no time was the situation particularly dangerous, biogas does not ignite so easily", they said.

It would probably be a mistake to discard this comment as a mere competence issue. It may well reflect widespread deep-seated simplistic and astonishingly naïve beliefs that "green" and "sustainable" fuels are less hazardous than their fossil fuel equivalents.

This may indeed be the nub of the problem with limited appreciation of the major accident hazard potential of biomass fuels.

4 ACCIDENT 2: FATAL DUST EXPLOSION AT WOOD PELLET FACILITY CAUSED BY WHEEL LOADER (REPEAT ACCIDENT)

4.1 The facility

A facility located in Aars, Denmark, produced wood pellets from a wide number of waste products, mostly shavings from furniture production, waste streams from the processing of grains, and energy crops [28].

Raw materials were received and stored in a building. Conveyors transported the raw materials to a mill in another building. After milling, a conveyor dropped the (wood) dust of a specific raw material into one of several storage bays. According to recipe, wheel loaders moved material from different bays to a mixing table, which fed the wood pellet press.

4.2 Dust explosion hazards

The wood dust in the storage bays is combustible and presents a risk of dust explosions. When handled, biomass pellets also generate fine dust in quantities that pose a risk for dust explosions. There are numerous reports of fires and explosions involving biomass pellet manufacturing and handling [8].

A dust explosion is the rapid combustion of fine particles of combustible material suspended in the air. Dust explosions can either be primary or secondary. A primary dust explosion occurs when a small suspension of combustible dust is ignited and explodes. A secondary explosion occurs when dust, which has been allowed to settle and accumulate on floors or other surfaces, is made airborne by the pressure wave of primary explosion and subsequently ignited by the slower moving flame front. Depending on the extent of the dust deposits, a weak primary explosion may cause very powerful secondary dust explosions.

Dust explosion hazards can be difficult to recognize by lay persons because the undisturbed atmosphere presents as free of dust and the workplace, when superficially inspected, may falsely appear dust free, overlooking dust deposits in e.g. hard to reach overhead areas.

Dust explosions have traditionally been difficult to deal with in industry. Part of the problem lies with the limited general understanding of the complex mechanism of dust explosions among plant operating personnel as well as corporate management.

4.3 Explosion in 2002

The facility began production of wood pellets in May 2001. The facility experienced a severe explosion in one of the storage bays on March 27, 2002. The roof was blown away, a light concrete wall was pushed outwards and a section of the wall had been toppled. The building was a complete loss. At the time of the explosion, a forklift driver was present inside. The forklift's cabin protected him from the effects of the explosion and he was able to flee unharmed.

The forensic technicians of the police investigated and concluded that an unidentified foreign body had entered the mill and generated a spark that ignited dust at the mill outlet. The fire then triggered a dust explosion in the storage bay. A specialist company was called to examine the spark detection system, but found no technical fault. Specialist fire scene investigators from an external company found no technical fault in the electrical installations which resulted in the same conclusion as the police – the explosion was caused by a spark.

The facility was rebuilt to the original blueprints, with minimal modifications.

4.4 Repeat explosion in 2010

On September 16, 2010, the facility experienced a new explosion, in the same building, and almost at the same location, when a Volvo wheel loader grabbed a bucket of wood dust in a storage bay. Within seconds, the floor in the bay was on fire and the flames almost instantly expanded to fill the entire compartment. The fire then triggered a dust explosion, which damaged the roof and blew out wall panels. The intense fireball killed the driver of the wheel loader. Another worker present inside the building was injured. The building was a complete loss (Fig. 5).

Already the following day, the police informed the public that that the cause of the explosion was identified. Due to a weld failure, the universal (cardan) joint, a power transmission component, broke loose under the vehicle and damaged nearby electrical cables. Electrical shorts and arching ignited airborne dust, which resulted in a combustible dust explosion, concluded the police [28].

The manager of the facility expressed emotion and disbelief, as the facility was in full compliance with the most recent norms and guidelines. In theory, this explosion should not be possible at all, he said.

As will be discussed later however, mere compliance with rules and regulations is no guarantee that the facility is safe.

Figure 5: Light damage. The many fiber cement roofing panels and wall panels that remained in place indicate that the dust explosion overpressure was modest. The dust explosion severity certainly could have been worse. Photo courtesy of Beredskab Vesthimmerland.

4.5 Real cause of the 2010 explosion

Later analysis [28] has identified serious flaws in the swift police investigation and has argued that the real cause was a failure by the driver to release the parking brake, which then overheated and ignited airborne dust.

This difference of argument is no banality, no trivial hair-splitting objection. If the cause is a random breakdown due to a hidden weld defect in a hard to reach mechanical component, very little indeed can be done to prevent recurrence. If the cause is an overheated parking brake however, there are major implications for accident prevention efforts because it suggests that this type of wheel loader is entirely unsuitable for locations where potentially explosive atmospheres of combustible dust exist.

In fact, it can be argued that the accident has broad learning potential because of the widespread usage of front loaders in environments with combustible dust, the innocent nature of the human error and the severity of the consequence.

4.6 Root cause not identified

The safety principles of the ATEX Directive direct attention to first, preventing the formation of flammable atmospheres; second, to reduce the chance of ignition, and third; to mitigate the severity of the consequences.

These principles pay intellectual debt to the earlier concept of inherent safety, which Kletz [29] was the first to clearly articulate. Ashford [7] later argued that inherent safety is similar in concept to pollution prevention. Inherent safety, sometimes referred to a primary prevention, relies on preventing the possibility of an accident. By comparison, secondary prevention relies on reducing the probability of an accident. Mitigation seeks to reduce the seriousness of the consequences, i.e. injuries and damage to the environment or property.

Ashford [30] observes that a bias in the engineering profession, a failure to address inherent safety and primary accident prevention, is one of the reasons why progress in eliminating accidents has been relatively slow.

Figure 6: Superficial investigation. A specialist police vehicle inspector examines the accident Volvo wheel loader shortly after the dust explosion. Tires are burned away and windows in the cabin melted. Upon learning that the universal (cardan) joint had failed, he erroneously concluded the explosion was caused by a mechanical failure due to a concealed weld defect. This finding closed the police investigation, as there was no indication of wrongdoing, only of bad luck. The inspector is looking in the wrong place for causes however. In fact, the underlying cause are in the storage bays just visible in the background. Why design the wood pellet facility with a buffer storage of 500 t of combustible wood dust? It was convenient to store the dust, but not essential to do so. Had the ATEX safety principles been applied, the buffer storage, and hence the fuel source and the potential for severe dust explosions, would have been eliminated. Source: Police investigation and the Danish Working Environment Authority.

Had the safety principles been applied during the investigation of the explosion in 2002, and again in 2010, attention would have been directed towards the soundness of having a buffer storage of 500 t of combustible wood dust (Fig. 7). It was convenient to store the dust, but not essential to do so. A superior design philosophy (from the point of view of safety) would be to mix raw materials according to production recipe and immediately process wood dust from the mill into pellets, eliminating the need for buffer storage, and eliminating a major source of fuel for dust explosions.

Figure 7: The real cause. Two of the storage bays that comprised the 500 t wood dust buffer storage. Photo courtesy of Beredskab Vesthimmerland.

4.7 Evidence of learning?

The 2002 explosion was a highly significant incident as it gave clear evidence of the inherent hazards of wood dust and was an opportunity to re-consider the soundness of having a large buffer storage of combustible wood dust. So was the 2010 explosion.

Both opportunities for learning were missed however, because the investigation was carried out by law enforcement officers, who were narrowly concerned with compliance with regulations, negligence, wrongdoing and culpability.

There is no evidence of new insights gained, no attempts to share basic accident information amongst workplace inspectors or amongst peers within the wood pellet industry. The accident investigation was superficial and information sharing absent. There is no evidence of learning whatsoever.

Had the company chosen to rebuild the facility, which this time they did not, a future repeat explosion in the storage bay area would be likely.

4.8 Ignorance

Law enforcement officers have neither training nor technical background in industrial accident investigation. In fact, their natural (but narrow) concern with negligence and wrongdoing is entirely misplaced in a perspective of learning from accidents. Assigning them to this task is a policy mistake.

Ignorance is also evident at the managerial level. As stated earlier, simplistic beliefs that compliance with rules and regulations ensures a high level of safety are misplaced and naïve. Had management requested a risk analysis? Was management aware of dust explosion cases elsewhere in industry? Probably not.

Ignorance is also evident at the designer level. Why design a facility with a 500 t buffer storage of combustible dust, thereby setting the scene for future serious dust explosions? The designer appears to have been concerned with secondary prevention, on reducing the probability of ignition. Was the designer aware of dust explosion cases elsewhere? Probably not. There is not much literature on the subject, there is little information sharing in the biomass industry.

4.9 Repeat accidents

A safety professional from a large Belgian company kindly shared notes on past accidents. It appears that a Volvo loader was involved in a "dust explosion in bunker followed by fire" on February 15, 2008. Another Volvo loader appears to have been involved in a "storage fire" in February 2010. The accidents appear to have taken place in Belgium or perhaps Holland. There is no further information.

This may be of some significance, because the Volvo loader in the 2010 explosion in Aars, Denmark, had a particular handbrake design, which made it susceptible to overheating if the driver failed to release the handbrake [28]. This is pure conjecture however, and the absence of data does not warrant any further speculation.

There was a dust explosion in a warehouse at Kalundborg Havn on March 7, 2012 while loading a truck with imported wood pellets. The truck driver, who was standing outside the warehouse next to his truck, sustained superficial burns. Pellets in the warehouse were moved with a wheel loader. Evidence indicates that the explosion took place inside a cup elevator however, and that the wheel loader was not involved. It was speculated that a foreign body had become stuck in the cup elevator, creating a spark. Wood pellets in bulk are carried in multi-purpose general cargo vessels and remnants of the vessel's prior cargo often end up in the pellet import. Hence, foreign bodies "wood, rods, metal parts of all kinds" are commonly discovered in the pellets.

5 ACCIDENT 3: FATAL CARBON MONOXIDE POISONING OF TWO SEAMEN

5.1 Carbon monoxide off-gassing hazard

Freshly produced wood pellets may emit a range of gasses such as carbon monoxide, carbon dioxide, methane and volatile organic compounds (VOCs) that can accumulate in storage confinements and reach dangerous levels [31]. The release of the highly poisonous and odorless carbon monoxide is of particular concern. In addition, freshly produced wood pellets may deplete the atmosphere in storage confinements of the oxygen required to sustain life [32].

This section examines the death of two seamen aboard the vessel AMIRANTE due to carbon monoxide poisoning.

5.2 Danger in cargo holds of marine vessel

Wood pellets are often shipped in bulk in marine vessels to their final destination. Problems with oxygen deficiency and dangerous levels of carbon monoxide in the cargo hold of marine vessels at sea have been known for over a decade [33] and the gasses have been responsible for many accidents.

The International Maritime Organization IMO/SOLAS has recently revised its guidance on entering enclosed spaces aboard ships in response to the ongoing problem of confined space incidents [34]. The guidance provides examples of enclosed spaces such as fuel tanks, ballast tanks, cargo pump rooms (used on e.g. chemical tankers), etc. – i.e. compartment that are not routinely accessed by ordinary seamen.

5.3 Gasses travel and reach rooms routinely accessed

In the Danish accident below, the seamen were poisoned, not in the cargo hold, but in a room, which was part of the normal working areas of the ship and routinely accessed. Important lessons of this accident are that dangerous gasses from the cargo hold can migrate and reach rooms considered safe.

As will be shown, this lesson and opportunities for learning were wholly missed. Accident descriptions in the public domain are hazy and basic facts are corrupted.

5.4 The accident

In the afternoon of July 15, 2009, during the passage of the Baltic Sea, two of the vessel's crew decided to enter the vessel's forepeak compartment. The forepeak is a stowage room at the bow of the ship, which is reached from the deck through a stairwell. The forepeak was used for miscellaneous storage: paints, ropes, etc.

The reason why the two seamen entered the forepeak is not known. Likely, the forepeak offered a convenient refuge for a clandestine cigarette break, out of sight of the tough captain.

Unknown to them, poisonous carbon monoxide gasses from the cargo hold had travelled to the forepeak through a crevice in a door that separated the front cargo hold compartment and the forecastle (Fig. 8). When the seamen did not show up for dinner, a search was initiated, which found them lifeless in the forecastle.

5.5 Investigation

The vessel was close to Danish territorial waters. The captain radioed the Danish authorities requesting immediate medical assistance and the vessel redirected to the port of Rønne, Bornholm. The police was waiting at the quay and began a standard crime scene procedure.

The criminal investigation found no evidence of criminal intent and was satisfied that the two seamen had received the proper safety instruction for working in enclosed rooms. The investigation was closed as there was no indication of wrongdoing, only of bad luck.

Important questions aimed at understanding why the accident happened were not raised. Were the crew aware of hazardous properties of the cargo? Was the forepeak considered a compartment with properties similar to those of enclosed cargo spaces? In all likelihood the crew were clueless about the danger [32].

5.6 Information sharing?

Because the police opened the case a crime scene investigation, the case was technically registered as a criminal case. In Denmark, criminal cases are kept confidential in order to protect the privacy of the individuals concerned. As a result, very little information, if any, relevant to accident prevention professionals is available in open sources.

5.7 Basic facts corrupted, no learning

It is true that there is sporadic and passing mention of the AMIRANTE accident in the wood pellet literature, e.g. [35], [36] but descriptions are hazy and basic facts are corrupted. This is also true for the papers produced by authors in Denmark. For example, a report [37] states that the seamen entered the cargo hold, which they did not, and a paper [38] states that they died from asphyxia, which is also wrong.

Because proper sharing of correct information about an accident is a basic precondition for learning it is concluded that learning processes were derailed at a very early stage.

Figure 8: The door in the forepeak compartment, which led the front cargo hold. The door had three closing hinges but only two were engaged. Gasses travelled from the cargo hold to the forepeak through a crevice where the third hinge (arrow) was not engaged. Source: Police investigation.

5.8 Systemic deficiency by design

The accident was investigated as a criminal case and the legal system is so designed that findings are kept out of reach of safety professionals and the general public. This approach has been criticized at an earlier occasion as being entirely misplaced in an accident prevention context [28]. It is a systemic deficiency by design – the bureaucratic judiciary system did not malfunction, it worked precisely as intended.

The flag state, St. Vincent & The Grenadines, did not investigate.

There is no evidence of learning whatsoever. Repeat fatal accidents later took place in Denmark [32].

6 CONCLUSION

This paper presents cases in support of the view that learning processes to prevent repeat biomass accidents are impeded, dysfunctional or entirely absent in Denmark.

- Knowledge about an explosion of a biogas digester passed into oblivion.
- A wood pellet facility experienced a devastating dust explosion. The accident was insufficiently investigated and root causes

relating to principles of inherent safety were not identified. As a result, a repeat explosion took place eight years later, this time with fatal outcome.

The case offers a textbook example of the truism that if accidents are not investigated, and root causes not identified, accidents recur.

- Knowledge about a fatal carbon monoxide accident was kept out of reach of safety professionals and the general public. Information in open sources are hazy and basic facts are corrupted.

Currently, there appears to be a substantial untapped potential for learning and information exchange. This potential should be exploited for the renewable energy and environmentally friendly biomass pellet industry also to become sustainable from a worker safety perspective.

This paper suggests that structural barriers exist at three levels:

(1) Production/managerial level: Biomass units are often installed at agricultural enterprises that are unfamiliar with gas processing technology, combustible dusts and poisonous gasses. Farmers assume tasks of process operators and gas engineer, tasks for which they have little or no training. The limited information available in open sources on accidents at Danish biogas units indicate that limited appreciation of process dangers and the finer details of ATEX hazards play a role.

(2) Institutional level. Accident investigations are tasked with the police. But law enforcement officers have neither training nor technical background in industrial accident investigation. In fact, their concern with negligence and wrongdoing is entirely misplaced in a perspective of safety. Assigning them to this task is a policy mistake. As a result, there is no information sharing, or learning, and repeat accidents take place.

(3) Policy level. Danish environmental ambitions are very high and the institutions involved are on a mission to fight global climate change problems in order to secure our common future. They are on a mission to save the world, nothing less. In such a global perspective, sight is easily lost of the environment of the workers. Safety issues are absent, downplayed or waved away in white papers and visionary policy reports, even though interventions can run counter to long established core principles of inherent safety and risk reduction [8], [39].

In 2016, Denmark topped the World Energy Councils' so-called trilemma index that takes into account three parameters: 1) environmental sustainability, 2) energy security, and 3) energy equity. Denmark ranked 1st on the World Energy Councils' global list, not only overall but also in terms of excellently balanced trilemma performance resulting in an outstanding triple–A grade [40].

The costs to society are breathtaking [8]. In this setting, the general failure to address safety risks appears particularly disheartening. Further research is needed to provide policy guidance on how to improve this situation.

There is currently no serious mechanism to register biomass accidents. At a practical level, a natural starting point would be to rectify this shortage of fundamental data. Systematic incident information capture and exchange, understanding the fundamental root causes, widely disseminating the lessons learned, and integrating these lessons learned into safe operations, are key to improving the safety performance of the expanding bioenergy industries.

Utmost care should be taken to avoid so-called media- shifting i.e. that the resolution of a problem within one domain, the environmental, creates a new problem in another, the workplace safety domain.

7 REFERENCES

[1] V. C. Moreno and V. Cozzani, “Major accident hazard in bioenergy production,” J. Loss Prev. Process Ind., vol. 35, pp. 135–144, 2015.

[2] C. Riviere and G. Marlair, “BIOSAFUEL (R), a pre-diagnosis tool of risks pertaining to biofuels chains,” J. Loss Prev. Process Ind., vol. 22, no. 2, pp. 228–236, 2009.

[3] S. Nair, “Identifying and managing process risks related to biofuel projects and plants,” HAZARDS XXII- Pap. 103, no. 156, pp. 331–338, 2011.

[4] S. S. Rivera, R. D. C. Olivares, P. A. Baziuk, and J. E. N. Mc Leod, “Assessment of Biofuel Accident Risk: A Preliminary Study,” in Proceedings of the World Congress on Engineering, 2015, vol. 2.

[5] G. E. Scarponi, D. Guglielmi, V. Casson Moreno, and V. Cozzani, “Assessment of Inherently Safer Alternatives in Biogas Production and Upgrading,” Aiche J., vol. 62, no. 8, pp. 2713–2727, 2016.

[6] F. H. Hedlund, “Do provisions to advance chemical facility safety also advance chemical facility security? - An analysis of possible synergies,” in OPCW International Meeting on Chemical Safety and Security. 8-9 November 2012. Proceedings, 2012, no. November, pp. 73–82.

[7] N. A. Ashford, “Industrial safety: the neglected issue in industrial ecology,” J. Clean. Prod., vol. 5, no. 1, pp. 115–121, 1997.

[8] F. H. Hedlund and J. Astad, “Solid Biomass Climate Change Interventions Examined in a Context of Inherent Safety, Media Shifting, and Emerging Risks,” Hum. Ecol. Risk Assess., vol. 21, no. 5, pp. 1410–1427, 2015.

[9] T. A. Kletz, What Went Wrong?: Case Studies of Process Plant Disasters. Houston, Texas: Gulf Professional Publishing, 1998.

[10] T. A. Kletz, Still going wrong!: case histories of process plant disasters and how they could have been avoided. Elsevier, 2003.

[11] R. E. Sanders, Chemical process safety: learning from case histories. Butterworth-Heinemann, 2015.

[12] F. H. Hedlund and H. B. Andersen, “Institutional support of learning from accidents: Some obstacles to getting a useful community-wide database in the EU,” in Society of Risk Analysis, SRA Europe, Annual Conference 2016, 2006, pp. 1–21.

[13] F. H. Hedlund, M. F. Nielsen, S. H. Mikkelsen, and E. K. Kragh, “Violent explosion after inadvertent mixing of nitric acid and isopropanol - Review 15 years later finds basic accident data corrupted, no evidence of broad learning,” Saf. Sci., vol. 70, pp. 255–261, 2014.

[14] T. A. Kletz, Learning from Accidents in Industry. London, U.K.: Butterworths, 1988.

[15] J. Reason, Managing the Risks of Organizational Accidents. Ashgate, 1997.

[16] Y. Dien, M. Llory, and R. Montmayeul, “Organisational accidents investigation

methodology and lessons learned," J. Hazard. Mater., vol. 111, no. 1, pp. 147–153, 2004.
[17] J. Rossen, "Alligevel røg skidtet i luften," Arbejdsmiljø, no. 1, pp. 13–16, 1991.
[18] F. H. Hedlund, "Eksplosion i rådnetank med biogas," Dansk Kemi, vol. 95, no. 12, pp. 12–15, 2014.
[19] T. S. Knudsen, "Gaseksplosion slamtank på rensningsanlæg (Vejle)," Brandværn, no. 1, pp. 27–28, 1991.
[20] A.-K. Lindberg, S. O. Hansson, and C. Rollenhagen, "Learning from accidents - What more do we need to know?," Saf. Sci., vol. 48, no. 6, pp. 714–721, 2010.
[21] "ARIA N°11345 - 12/03/1997 - Italie - 00 - Peschiera Del Garda," La base ARIA (Analyse, Recherche et Information sur les Accidents). Ministère du développement durable - DGPR / SRT / BARPI, 2015. [Online]. Available: www.aria.developpement-durable.gouv.fr. [Accessed: 12-Aug-2015].
[22] "Att skydda och rädda liv, egendom och miljö: Handbok i kommunal riskanalys inom räddningstjänsten," Räddningsverket, Karlstad, Sweden, 1989.
[23] G. E. Scarponi, D. Guglielmi, V. Casson Moreno, and V. Cozzani, "Risk Assessment of a Biogas Production and Upgrading Plant," Chem. Eng. Trans., vol. 43, pp. 1921–1926, 2015.
[24] S. R. Secondo Cividino et al., "BiogasAgriAtex, new methods of risk assessment explosion on biogas plants," Appl. Math. Sci., vol. 8, no. 129–132, pp. 6599–6619, 2014.
[25] "Verpuffung in Biogasanlage - Zwei Personen verletzt," Märkische Oderzeitung, 25-Jul-2011.
[26] B. Pietrangeli, R. Lauri, and P. A. Bragatto, "Safe operation of biogas plants in Italy," Chemical Engineering Transactions, vol. 32. Italian Association of Chemical Engineering - AIDIC, pp. 199–204, 2013.
[27] P. Gupte, "Sludge Coats Shore After L.I. Explosion; Youth, 16, Missing; Explosion of Two Sewage Tanks Apparently Kills L.I. Youth, 16; Heard Three Miles Away," New York Times, pp. A1, D17, 06-Jun-1976.
[28] F. H. Hedlund, J. Astad, and J. Nichols, "Inherent hazards, poor reporting and limited learning in the solid biomass energy sector: A case study of a wheel loader igniting wood dust, leading to fatal explosion at wood pellet manufacturer," Biomass and bioenergy, vol. 66, pp. 450–459, 2014.
[29] T. A. Kletz, Cheaper, safer plants. Or wealth and safety at work. Notes on inherently safer and simpler plants. Rugby, Warwickshire, England: The Institution of Chemical Engineers (IChemE), 1984.
[30] N. A. Ashford, "Reducing physical hazards: encouraging inherently safer production," in Designing Safer Chemicals. Handbook of Green Chemistry, R. Boethling, A. Voutchkova, and P. Anastas, Eds. Wiley Online Library, 2012, pp. 485–500.
[31] G. Thek and I. Obernberger, The pellet handbook: the production and thermal utilization of biomass pellets. Routledge, 2012.
[32] F. H. Hedlund and Ø. J. Hilduberg, "Fatal Accidents During Marine Transport of Wood Pellets Due to Off-gassing – Experiences from Denmark," in Biomass Volume Estimation and Valorization for Energy, J. S. Tumuluru, Ed. Rijeka, Croatia: InTech, 2017, pp. 73–97.
[33] S. Melin, U. Svedberg, and J. Samuelsson, "Emissions from wood pellets during ocean transportation (EWDOT). Research report," Wood Pellet Association of Canada (lead), 2008.
[34] "IMO Revised Recommendations for Entering Enclosed Spaces Aboard Ships. IMO Resolution A.1050(27)," The International Maritime Organization (IMO), 2012.
[35] S. Gauthier, H. Grass, M. Lory, T. Krämer, M. Thali, and C. Bartsch, "Lethal carbon monoxide poisoning in wood pellet storerooms—two cases and a review of the literature," Ann. Occup. Hyg., vol. 56, no. 7, pp. 755–763, 2012.
[36] U. Svedberg and A. Knutsson, "Faror och hälsorisker vid förvaring och transport av träpellets, träflis och timmer i slutna utrymmen. Kunskapsöversikt. Rapport 2011:2 (in Swedish). [Hazards and health risk with storage and transport of wood pellets, wood shavings and timber in enclosed," Arbetsmiljöverket, Stockholm, Sweden, 2011.
[37] W. Stelte, "Guideline: Storage and handling of wood pellets. Resultat Kontrakt (RK) report," Danish technological institute, Taastrup, Denmark, 2012.
[38] B. K. Sovacool et al., "Balancing safety with sustainability: assessing the risk of accidents for modern low-carbon energy systems," J. Clean. Prod., vol. 112, pp. 3952–3965, 2016.
[39] F. H. Hedlund, "LNG safety – an emerging and ignored issue in the climate change debate," Eur. Saf. Reliab. Assoc. Newsl., no. September, p. 2, 2014.
[40] World Energy Council, "World Energy Trilemma, 2016. Benchmarking the sustainability of national energy systems," London, U.K., 2016.

8 ACKNOWLEDGEMENTS

This article has been produced as voluntary work and has not received any funding. Opinions expressed are those of the author, not of his employer or organization. I'm grateful to COWI for covering the conference fee.